

Science & Technology

REVIEW

July/August 2001



U.S. Department of Energy's
Lawrence Livermore
National Laboratory

The State of the Stockpile

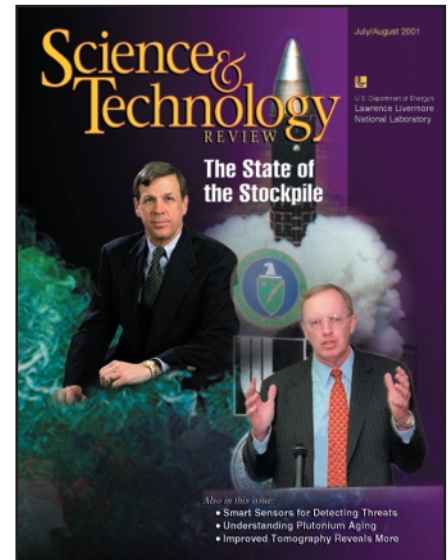


Also in this issue:

- Smart Sensors for Detecting Threats
- Understanding Plutonium Aging
- Improved Tomography Reveals More

About the Cover

This month's feature on Annual Certification, beginning on p. 4, describes the process of evaluating the nation's nuclear arsenal to determine if underground nuclear testing is necessary to resolve any stockpile safety or reliability issues. Lawrence Livermore is among the organizations responsible for this certification. Each year, Livermore's Director Bruce Tarter (left) must sign a letter attesting to the condition of Livermore-designed nuclear weapons. General John Gordon (lower right) administers the National Nuclear Security Administration (NNSA) of the Department of Energy. NNSA is the repository of all national security activities for DOE.



Cover design: George Kitrinos

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy's National Nuclear Security Administration. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published 10 times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Contents

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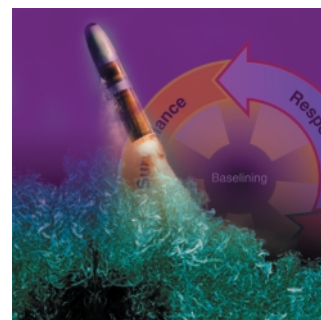
Features

3 National Security Is Our Unifying Theme

Commentary by C. Bruce Tarter

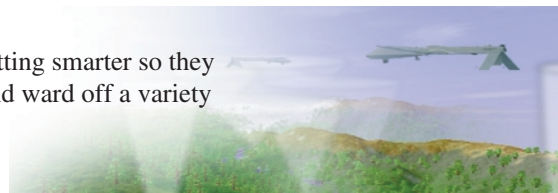
4 Annual Certification Takes a Snapshot of Stockpile's Health

The annual assessment of the stockpile is central to Livermore's mission and vital to national nuclear security.



11 Sensing for Danger

Networked sensors are getting smarter so they can better detect, track, and ward off a variety of threats.



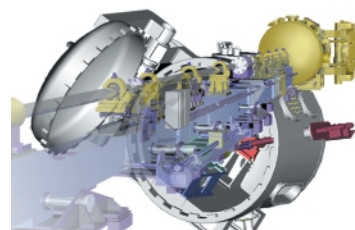
Research Highlights

18 It's the Pits in the Weapons Stockpile

Getting old is serious business for nuclear weapon pits.

21 Looking into the Shadow World

New software and better radiography are yielding higher-quality tomographs.



Departments

2 The Laboratory in the News

26 Patents and Awards

29 Abstracts

More complexity in global climate prediction

Researchers Bala Govindasamy, Ken Caldeira, and Philip Duffy of Livermore's Atmospheric Science Division reported in a recent issue of *Geophysical Research Letters* that cooling temperatures recorded on Earth from 1000 to 1900 could be attributed to changes in land use instead of to natural variations in climate.

Duffy, leader of Livermore's climate and carbon-cycle modeling group, said that "the main way humans influence climate is by burning fossil fuels, which make greenhouse gases. But we also suspected that large-scale changes in land use contributed to climate changes." To test their theory, the researchers performed computer simulations of two scenarios for climate development: one simulating natural vegetation conditions and one accounting for deforestation caused by agricultural land use.

During the 900-year period covered by the simulations, the regions that cooled more were the ones where there was deforestation and dense human activity. Over land in the U.S., there was a cooling of about 0.41 kelvin. The researchers explained that the darker colors of forests tend to absorb sunlight, thus trapping heat on Earth, while the fields of grain or corn in agricultural land are lighter-hued and reflect solar rays back into space. Duffy said, "People talk about planting trees as a way to slow global warming, [but our study] suggests that may not work. It . . . might not be a good idea."

Caldeira commented, "This is an example of inadvertent geoengineering—we changed the reflectivity of the Earth and have probably caused a global cooling in the past. This is now probably being overwhelmed by our greenhouse gas emissions."

Contact: Philip Duffy (925) 422-3722 (duffy2@llnl.gov).

Lab's plague detection system gets results fast

Using a DNA-based test system developed at Livermore, biologists at Northern Arizona University were able to detect an outbreak of plague in prairie dogs so quickly that they could issue health warnings within hours.

"If we hadn't gotten the warning out, someone could have gotten sick," said Paul Keim, a microbiology professor who used the test. "The speed of the test made all the difference."

The outbreak was the first time that the Livermore detection system was used to test for a disease in the environment—in this case, *Yersinia pestis*, the bacteria that cause plague, which is carried to fleas from prairie dogs. The system could accurately and speedily test for *Y. pestis* bacteria because it was based on

the bacteria's DNA signature, which had been developed by Livermore scientists. Flea samples were subjected to the test and within six hours, the testing team had four positive readings and had initiated a series of preventive messages to the public.

The development of the *Y. pestis* signature is part of Livermore's work on methods to monitor, detect, and counter infectious diseases or bioterrorism agents. Of its use in the plague outbreak, Livermore biomedical scientist Paula McCready said, "It's very exciting, and it made all the hard work we went through worthwhile. We did a lot of analysis to make sure these DNA signatures were unique to *Yersinia pestis* and nothing else in the environment."

The use of genetic signatures to speedily monitor the spread of infectious diseases is based on a DNA detection method called polymerase chain reaction, or PCR. "Because at least some of a pathogen's genes and its DNA are unique to it, PCR can be used to detect even a single germ in a very specific fashion," said Keim. "The basic technology has been applied to many different diagnostic problems, but you have to know what the specific DNA codes are for each. Without these, it is like a computer without software. LLNL provided the DNA codes to detect plague."

Contact: Paula McCready (925) 422-5721 (mccready2@llnl.gov).

Livermore will extend life of cruise missile warhead

Officials at the National Nuclear Security Administration of the Department of Energy have approved an agreement, signed by the directors of the Livermore, Los Alamos, and Sandia national laboratories, to assign the responsibility of refurbishing the W80 warhead to Livermore. Originally developed at Los Alamos, the W80 is carried by cruise missiles.

Los Alamos weapons scientists will continue to be responsible for the Mod 0 and Mod 1 warheads in the stockpile. Livermore, together with Sandia/California, will develop the next round of modifications, dubbed Mod 2 and Mod 3, as well as all future changes to extend the stockpile life of the warhead.

The assignment of responsibilities seeks "to accomplish a more balanced workload at the nuclear laboratories and tend to the current needs of the national stockpile." The effort is expected to last five years, and an estimated 30 Livermore researchers will form the core group for the refurbishment project.

Contact: Don Johnston (925) 423-4902 (johnston19@llnl.gov).

(continued on p. 25)



National Security Is Our Unifying Theme

NATIONAL security is the one unifying mission of Lawrence Livermore National Laboratory. In that respect, no element of our mission is more important than Annual Certification, a formal assessment of the nation's nuclear stockpile. As Laboratory director, my role in Annual Certification includes sending a letter to the secretaries of Energy and Defense, stating whether a resumption of underground nuclear testing is warranted to resolve a safety or reliability issue in a Livermore-designed nuclear weapon system. I make that determination following a thorough review of Lawrence Livermore's stockpile stewardship activities.

As described in the article beginning on [p. 4](#), the complex Annual Certification process involves experts at Lawrence Livermore, Los Alamos, and Sandia national laboratories; Department of Defense agencies; and the National Nuclear Security Administration (NNSA), a semiautonomous agency that began operation in March 2000. Congress created NNSA as a way to place under one roof all the national security activities of the Department of Energy.

NNSA's responsibilities include maintenance of a safe, secure, and reliable stockpile of nuclear weapons and associated materials capabilities and technologies; promotion of international nuclear safety and nonproliferation; and management of the naval nuclear propulsion program. More than three-quarters of our funding comes under the auspices of NNSA. Practically speaking, NNSA is our "landlord."

General John Gordon, NNSA's administrator, has visited the Laboratory several times, and he was on hand to help celebrate our first Science Day in March and, on April 10, the final certification of the W87 weapon system refurbished through the Life Extension Program. During the March visit, Gordon spoke of the need for scientists and security experts to collaborate so that both missions operate at optimum levels at the national laboratories.

General Gordon has had three essential tasks to fulfill: build a long-term, stable budget for the agency and its programs; create a new organization from scratch; and find good people to fill the jobs. He's already presented a five-year budget to

Congress that received high praise. And he's adopted an organizational structure that mirrors that of the national laboratories. Within this framework, just as most of Livermore's operational and institutional oversight is done in the Director's Office, similar responsibilities are handled by NNSA at its headquarters. The research directorates in which most of our programmatic and technical work is performed would correspond to NNSA's Defense Programs and Defense Nuclear Nonproliferation organizations.

All of us at Lawrence Livermore are looking forward to close and effective relations with our new Washington sponsor. To aid that effort, I've named Michael Anastasio, formerly associate director of Defense and Nuclear Technologies, to the new post of deputy director for Strategic Operations. Mike will be working closely with NNSA managers. As the former head of the directorate most responsible for stockpile stewardship, Mike has the background and experience that can only strengthen our interactions with NNSA.

■ C. Bruce Tarter is director of Lawrence Livermore National Laboratory.

Annual Certification Takes a Snapshot of Stockpile's Health

*The nuclear
arsenal gets a
yearly checkup.*

Lawrence Livermore Director C. Bruce Tarter

Lawrence Livermore National Laboratory



AS director of Lawrence Livermore, Bruce Tarter faces a host of significant responsibilities: directing the overall research activities of more than 8,000 employees, managing a budget of more than \$1 billion, and testifying before Congress about key national security issues. Yet nothing is more important than one yearly task, that of signing a letter stating whether nuclear weapon systems with Livermore designs have major safety or reliability issues that must be resolved with underground nuclear testing.

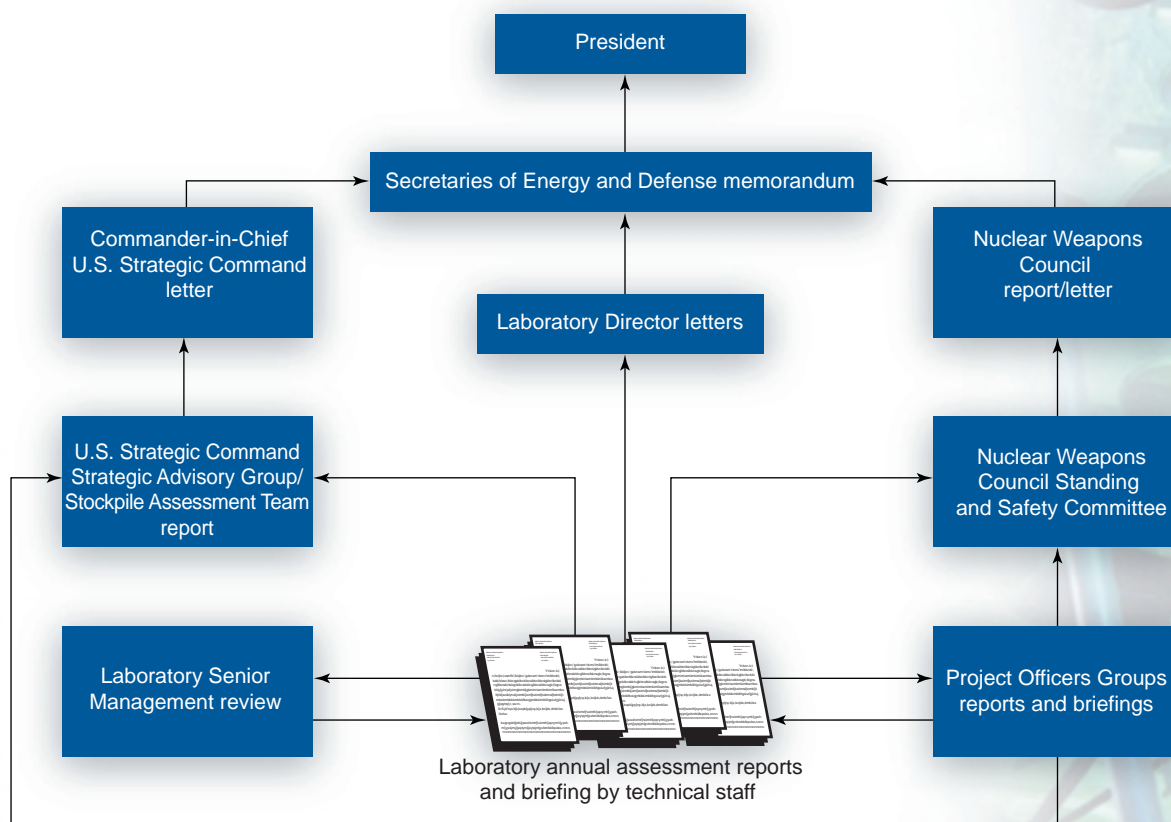
The director's letter, and those from the directors of the Department of Energy's other two national security laboratories, Sandia and Los Alamos,

are part of an exhaustive, largely standardized process called Annual Certification. The process is a formal assessment and reporting of the status of the nation's stockpile of nuclear warheads and bombs. The first Annual Certification was completed in February 1997, and the sixth is under way.

The Annual Certification process plays a central role in ensuring that everyone in the nuclear enterprise, from top to bottom, has a common understanding of the health of the stockpile. This understanding is based on thorough technical evaluations by staff at the Livermore, Los Alamos, and Sandia national laboratories; statements by their directors; and findings by the

joint DOE National Nuclear Security Administration (NNSA)/Department of Defense (DoD) Project Officers Groups (POGs), the commander-in-chief of the Strategic Command, and the Nuclear Weapons Council. Ultimately, the secretaries of Energy and Defense report in a written memorandum (classified by law beginning in 2000) to the president concerning the safety and reliability of the stockpile and whether a resumption of nuclear testing is needed. Several other agencies, groups, and advisory panels also play important roles.

"Annual Certification is a review of the status of the nuclear stockpile based on the results of ongoing stockpile



The Annual Certification process is based on technical evaluations by Lawrence Livermore, Los Alamos, and Sandia national laboratories; statements by their directors; and findings by the joint DOE National Nuclear Security Administration/Department of Defense Project Officers Groups, the commander-in-chief of the Strategic Command, and the Nuclear Weapons Council and its Standing and Safety Committee. The secretaries of Energy and Defense report in a memorandum to the president on the safety and reliability of the stockpile and whether a resumption of nuclear testing is needed.

stewardship work,” says Jim Tyler, physicist and program manager for stockpile support. Tyler, who leads the annual effort at Lawrence Livermore, explains that Annual Certification is a “snapshot” of the nation’s stockpile, drawing on all aspects of the Stockpile Stewardship Program. Director Tarter compares it to an annual physical.

Tyler notes that a common confusion arises from the term “certification,” which has a special meaning to nuclear stockpile managers. Weapons are certified when they are originally built or when a significant modification is made to them, and this certification doesn’t expire each year.

Annual Certification, however, is an assessment of the current stockpile and not a formal certification of the stockpile weapons. “We don’t recertify the stockpile warheads and bombs every year. We put together an assessment of the status of the stockpile and present it to the government,” he explains.

Process Starts at the Labs

At the three national security laboratories, the Annual Certification process begins in January with the drafting of nine Annual Assessment Reports. The nine reports correspond to the nine nuclear weapon designs that comprise the nation’s nuclear stockpile (see [box on p. 7](#)). Each report reviews the status of a particular warhead or bomb system. The reports also include a description of each system’s current role and planned future role in the nation’s stockpile and any ongoing or planned modifications. A key portion of each report discusses whether nuclear testing is warranted.

Lawrence Livermore and Sandia/California staffers prepare four reports, called the California reports,

that describe the status of the four nuclear weapons designed by their two laboratories: the W62, W84, and W87 warheads and the B83 bomb. These four weapon systems have been or are expected to remain in the stockpile well past their originally anticipated lifetimes; in fact, the W62 is already well past its lifetime. Los Alamos and Sandia/New Mexico experts compile the drafts of the New Mexico reports on the five stockpiled nuclear weapon systems designed at Los Alamos and Sandia.

For the dozens of Livermore weapons specialists involved in Annual Certification, the draft report process involves a comprehensive review of the Laboratory’s stockpile stewardship activities pertaining to each of the four weapon systems. Stockpile stewardship is the program managed by NNSA to maintain the nation’s nuclear arsenal in the absence of nuclear testing by using improved scientific and engineering tools. The program was created in the early 1990s in response to the cessation of underground nuclear testing (see [box on p. 8](#)). “The quality of our Annual Assessment Reports can be no better than the quality of our day-to-day stockpile stewardship effort,” says Tyler.

A major element of stockpile stewardship is regular surveillance of stockpile weapon systems to evaluate the evolving status of the warheads and bombs as they age. Livermore has



The W84 warhead, now inactive, was designed for the Ground Launched Cruise Missile, seen in this test launch.



A test launch of the Minuteman III ICBM (intercontinental ballistic missile), which is equipped to carry the W62 warhead.



A mock B83 bomb is dropped from a B-2 bomber in this flight test. Such tests are conducted as part of stockpile surveillance activities.

special responsibilities for the surveillance of the four weapon systems that feature its nuclear designs. These responsibilities include assessing the systems' safety and potential performance and planning for any refurbishment that might be needed in the future.

In assembling the draft reports, Laboratory managers collect and analyze information from surveillance activities as well as physics, engineering, and chemistry and materials science data from a complement of stockpile stewardship activities called "baselining." Lawrence Livermore scientists, engineers, and technicians use baselining tools such as advanced computer simulations, component-level experiments, subcritical experiments involving plutonium and high explosives at the Nevada Test Site, nonnuclear experiments at Livermore's remote Site 300, and analysis of historical data from past nuclear tests. Baselining supports surveillance work assessments and response decisions, Tyler says.

By the end of March, after thorough internal review by technical leaders, the

initial drafts of the nine Annual Assessment Reports are distributed among the three laboratories and NNSA personnel for review and comment. In this way, stockpile issues are reviewed and discussed by appropriate people throughout the NNSA community instead of only by scientists and engineers at the laboratories that designed the original weapon and who have primary responsibility for its surveillance. Indeed, the use of various forms of peer review has become a key component of many stockpile stewardship efforts because it minimizes the potential for unrecognized errors by one group or organization.

Comments and questions about the draft reports are discussed at a two-day meeting at Sandia/New Mexico in mid-April that is attended by representatives from NNSA and the laboratories. Livermore sends about two dozen people to the meeting, including managers, physicists, engineers, and materials experts. During this meeting, each weapon system and its draft report are reviewed separately. The sessions are

led by the cognizant system managers from Sandia and either Livermore or Los Alamos. The managers respond first to submitted questions and concerns and then ask for additional questions from attendees. "It's not a meeting to force consensus but rather an opportunity to air issues and hear other viewpoints," comments Tyler.

Drafts Receive DoD Review

By late April, the California and New Mexico teams complete amended drafts of the laboratories' Annual Assessment Reports. These drafts, which incorporate comments from the New Mexico meeting, are provided to the Project Officers Groups (POGs) as input for their own Annual Certification Assessment Reports. "A POG is a group of NNSA and DoD personnel who



A test launch of the Peacekeeper ICBM, which is equipped to carry the W87 warhead.

Lawrence Livermore–Designed Warheads in the U.S. Stockpile

Warhead/ Bomb Mark	Description	Carrier	Primary Use	Military Service
W62	ICBM (intercontinental ballistic missile) warhead	Minuteman III ICBM	Surface to surface	Air Force
B83-0/1	Strategic bomb	B-52, B-2 bombers	Air to surface	Air Force
W87	ICBM warhead	Peacekeeper ICBM	Surface to surface	Air Force
W84 (inactive)	Cruise missile warhead	None at present (formerly Ground Launched Cruise Missile)	None at present	Air Force

Annual Certification Based on Stockpile Stewardship

In 1995, President Clinton announced that the nation would begin a program called Stockpile Stewardship. This program would use science-based methods to assess the safety and reliability of the nation's nuclear stockpile in the absence of nuclear testing. The president also called for a new Annual Certification procedure as a formal way to periodically assess and report the status of the stockpile under the new program.

"I am today directing the establishment of a new annual reporting and certification requirement that will ensure that our nuclear weapons remain safe and reliable under a comprehensive test ban," President Clinton declared. Under this arrangement, the secretaries of Defense and Energy receive annual formal assessments from directors of the three weapons laboratories—Livermore, Los Alamos, and Sandia—the commander-in-chief of the U.S. Strategic Command, and the Nuclear Weapons Council.

Some experts have compared the challenges of stockpile stewardship to the World War II Manhattan Project to develop the atomic bomb or the Apollo program to safely land a man on the moon. The reason, in part, is that nuclear weapons are extremely complex devices. Many factors greatly influence the performance of thousands of components in ways that are not fully understood.

Livermore's stockpile stewardship work involves researchers from the Defense and Nuclear Technologies, Engineering, National Ignition Facility Programs, Chemistry and Materials Science, Computation, and Physics and Advanced Technologies directorates. These researchers rely on data from past nuclear tests, past and present nonnuclear tests, fundamental science and component-level experiments, surveillance of actual weapons withdrawn from the stockpile, and advanced simulations. This approach has enabled them to successfully address stockpile issues.

Weapons of Good Pedigree

The weapons intended for the enduring stockpile all have good pedigrees—they went into the stockpile with blue-chip credentials. However, regular inspections of aging components have led to modifications of some weapons in the stockpile.

As with all nuclear weapons, those designed at Livermore use a wide range of materials. Changes related to aging and to interactions among materials have been observed in a number of systems and in unexpected ways, especially as systems age beyond their design lifetimes. For example, organic materials such as plastics decompose, metal joinings corrode, and many materials change properties unpredictably in response to radioactive environments.

When modifications are deemed necessary, scientists and engineers assess options for refurbishing or replacing specific

components, including new production and fabrication processes and materials. Modification actions must then be formally validated. At Livermore, scientists and engineers also have broader responsibilities to develop assessment capabilities, technologies, and processes that contribute to maintaining the safety and reliability of all stockpiled weapons.

Livermore scientists use a unique collection of tools to examine and test the many materials that make up a weapon. Many of these tools were developed or modified at Livermore. For example, one tool samples gases inside a weapon's interior environment to identify potential material interactions, monitor aging indicators, and screen for defects such as incompletely cured adhesive.

Process Requires Special Studies

One special effort for stockpile surveillance is monitoring the chemical high explosives that are detonated to implode a plutonium pit. Livermore scientists are studying the long-term stability of the complex organic molecules making up high explosives. They examine samples from the stockpile for changes in appearance and texture; measure their physical, chemical, and mechanical properties; and conduct performance tests on them.

Likewise, a focused effort is under way to better understand the aging mechanisms of plutonium pits because this understanding is crucial to predicting weapon performance. (See "It's the Pits in the Weapons Stockpile," pp. 18–20.) In the same vein, data from underground subcritical experiments at the Nevada Test Site contribute information on the fundamental nature of plutonium and the effects of aged plutonium.

The knowledge gained from examining nuclear weapon components and materials and their aging mechanisms is used to increase the fidelity of computer codes. Realistic computer simulations then can predict the mechanisms of material failure and reveal the likely effects of substituting different materials. NNSA's Accelerated Strategic Computing Initiative is rapidly pushing computational power far beyond present capabilities so scientists can better simulate the aging of nuclear weapons and predict their performance.

NNSA is also investing in advanced experimental facilities such as the National Ignition Facility, under construction at Livermore, and the Dual-Axis Radiographic Hydrodynamic Test Facility, under construction at Los Alamos. The new capabilities will be needed to address the most challenging stockpile performance issues that can be expected to arise as weapons systems continue to age.

manage a particular nuclear warhead or bomb,” says Tyler.

POG meetings, held at various locations in early May, include a review of the DoD aspects of each weapon system, for example, how a DoD reentry vehicle integrates with the NNSA warhead components it contains. In that respect, POG meetings review weapon systems in a broader context than earlier meetings attended by just DOE, NNSA, and laboratory staff. Livermore representatives return from the POG meetings with new comments for inclusion in the laboratories’ final Annual Assessment Reports.

During May, Livermore senior managers also review the status of the four Livermore stockpile systems. The weapon system managers and technical staff give extensive briefings on these systems to the associate director for Defense and Nuclear Technologies, covering all the technical details that could have bearing on the current or future health of the system.

In June, Livermore managers coordinate their Annual Certification results to NNSA. Following this briefing, Laboratory scientists make a formal presentation to the Stockpile Assessment Team of the U.S. Strategic Command (STRATCOM), the DoD unified command agency for the nation’s nuclear forces. This forum provides an opportunity for the entire national security community to review the information together. The Stockpile Assessment Team is STRATCOM’s advisory panel for stockpile status and issues. The June meeting supports STRATCOM’s Annual Certification Report and the letter to the Secretary of Defense signed by the commander-in-chief, U.S. Strategic Command (CINCSTRAT). The meeting is also attended by representatives from NNSA and DoD agencies and by the Panel to Assess the Reliability, Safety and Security of the United States Nuclear

Stockpile. This panel, established by law, is headed by former Livermore director John S. Foster. The meeting gives valuable feedback to Livermore managers about their stockpile stewardship roles, says Tyler.

Briefings for the Director

During the summer, the director receives extensive briefings on the status of the Livermore-designed stockpile systems in preparation for his letter to the secretaries of Energy and Defense. The briefings, presented by weapon system managers and attended by other senior Livermore weapons scientists and managers, reflect comments and issues raised during the previous meetings. This year, for the first time, members of the University of California’s National Security Panel will also attend.

After the director’s review, the final versions of the four Lawrence Livermore/Sandia Annual Assessment Reports are issued late in July. For each report, a transmittal letter is signed by the associate director for Defense and Nuclear Technologies and by the cognizant Sandia vice president. These final reports are sent to other laboratories and to NNSA, which forwards them to the POGs, appropriate DoD agencies, and the White House.

The directors’ letters to the secretaries of Energy and Defense are issued in the fall. In his letter, the Livermore director states whether he believes a resumption of nuclear testing is warranted for Livermore-designed systems.

The CINCSTRAT letter to the Secretary of Defense is also transmitted in the fall. The Nuclear Weapons Council, established by law to coordinate all nuclear weapons activities for the nation, now enters the picture. The council, composed of senior officials from the NNSA and DoD, issues its report on the stockpile in November or December. It does so after receiving input from its Nuclear Weapons Council Standing and Safety Committee, which reviews and considers the reports, briefings, and letters from the laboratories, POGs, and STRATCOM.

The Annual Certification Memorandum from the secretaries of Energy and Defense to the president is issued after their staffs have analyzed the material submitted by the laboratories and other agencies. Beginning in 2000, this memorandum is classified to help ensure that accurate technical assessments can always be included. (See box with the 1999 memorandum on p. 10.)



Annual Certification is based on ongoing stockpile stewardship work. The work consists of surveillance, assessment, response, and baselining. Baselining, in turn, consists of day-to-day activities such as computer simulations, subcritical experiments of plutonium at the Nevada Test Site, and nonnuclear tests at Livermore’s remote Site 300.

Central Role

Five cycles of the Annual Certification have now been completed, and this yearly review has assumed a central role in stockpile stewardship. On many levels, the Annual Certification uniquely benefits the nation's security and offers advantages to Livermore stockpile stewards, says Tyler. First, the Laboratory's stockpile stewardship activities receive "a good scrubbing" from its own people, other NNSA laboratory experts, and knowledgeable people from DoD agencies and outside panels. The process generates valuable feedback and "sharpens our stockpile stewardship activities," Tyler says. By the same token, NNSA and DoD agencies learn firsthand from the laboratories about current stockpile status. The interactions help ensure that the nation's nuclear security community has a common understanding of the status of the nuclear stockpile.

—Arnie Heller

Key Words: Annual Certification, National Nuclear Security Administration (NNSA), Nuclear Weapons Council, Project Officers Groups (POGs), stockpile stewardship, subcritical experiments, U.S. Strategic Command.


For further information contact James Tyler (925) 424-3957 (tyler1@llnl.gov).

Annual Certification Memorandum for 1999

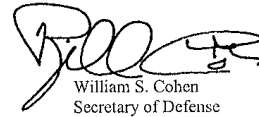
MEMORANDUM FOR THE PRESIDENT

SUBJECT: Nuclear Stockpile Certification

In response to your direction to conduct an annual certification of the nuclear weapons stockpile, we have thoroughly reviewed the safety and reliability of the stockpile. The nuclear stockpile has no safety or reliability concerns that require underground nuclear testing at this time. Problems that have arisen in the stockpile are being addressed and resolved without underground nuclear testing to ensure the stockpile remains safe and reliable. In reaching this conclusion, we have obtained the advice of the Directors of the National Weapons Laboratories, the Commander in Chief, United States Strategic Command, and the Nuclear Weapons Council. We will continue to inform you annually on the safety and reliability of the nuclear weapons stockpile in the absence of underground nuclear testing, and in the context of the DOE's Stockpile Stewardship Plan.


Bill Richardson
Secretary of Energy

Executed: April 5, 2000

 MAR 22 2000
William S. Cohen
Secretary of Defense

About the Scientist



JAMES TYLER received a B.A. in physics from Vanderbilt University in 1966 and a Ph.D. in nuclear physics from the University of Wisconsin at Madison in 1973. He joined the Laboratory in August 1973. At Livermore, he has designed nuclear explosives, managed two warhead development projects, managed studies of possible future warheads, and been on staff supporting the Military Applications Office and the Defense and Nuclear Technologies (DNT) Directorate. At present, Tyler is the program manager for Stockpile Support in DNT. As such, he is involved in extensive interface activities between the Livermore nuclear weapons program and corresponding organizations in the National Nuclear Security Administration, the Department of Defense, and the Los Alamos and Sandia national laboratories. A major part of this work is the management of Livermore's yearly efforts supporting the process for Annual Certification of the nation's nuclear stockpile. Tyler is also the program manager for the Evaluation and Planning Program, which comprises systems analysis and weapons effects studies.

Sensing for Danger

Correlated sensor networks can help fight against nuclear terrorism and other threats.



PICTURE this scenario: A terrorist carefully negotiates city streets, moving ever closer to his target, an air force base on the outskirts of town. In the rear of his van, a homemade bomb—containing plutonium and high explosives—waits for the signal to explode. As one of the “good guys,” you’ve received information that the attack is imminent, but your sources don’t know its timing, the direction from which the vehicle will come, or what route it will take. What can you do to detect, identify, and track the van and its contents so that you can prevent the attack? At Lawrence Livermore, researchers in the Nonproliferation, Arms Control, and International Security (NAI) Directorate have been exploring responses to this threat and others like it.

The researchers are focusing on systems for detecting and tracking threats. The systems go by many names—correlated sensor networks, wide-area tracking systems, sensor or network fabrics—but the concept behind them is the same. Take a number of wireless sensors (for instance, seismic, magnetic, pressure, acoustic, nuclear, or particle-counting), tie them together with a communications network,

develop a scheme for fusing the data (that is, converting the data into forms easily interpreted by users), and make the system easy to deploy.

Such correlated sensor networks can help detect a nuclear terrorist attack, track the movement and characteristics of a wildfire, assist military operations in taking out a target, determine earthquake damage to large structures such as bridges, and even protect the president.

The Power of Networking

The power of correlated sensor systems arises from their networked

nature. “You could ask, ‘Why not just use a bunch of stand-alone sensors?’” says Rob Hills, acting leader of the Tactical Systems Section in NAI. “Part of the problem is that many sensors, particularly those that detect nuclear signals such as gamma rays and neutrons, have a hard time differentiating between a ‘hit’ and normal variations in the background radiation. And to compound the challenge, the farther one moves away from a nuclear source, the weaker the signals become.” Sid Niemeyer from the NAI directorate office agrees, saying that “Weapons-usable nuclear materials are difficult to

detect under circumstances of unconventional nuclear warfare, as nuclear terrorism is sometimes called. As the distance between a detector and source increases, the radiation signature quickly fades into the background caused by other artificial and natural sources.”

One solution is to network the sensors, that is, have them share the information they gather. “Networked sensors allow the user to ‘see’ more by creating a more complete picture of the situation, something that stand-alone sensors cannot do,” says Niemeyer. For this article’s opening scenario, for instance, a correlated sensor network

The Challenge—Smaller, Smarter, More Energy-Efficient Sensors

Most of today’s wireless sensors are big and heavy. They have large power requirements and limited intelligence. Thus, large networks of such sensors are impractical. In the Nonproliferation, Arms Control, and International Security (NAI) Directorate, researchers are working to create sensors that use less energy, are more intelligent, and scale better to large networks.

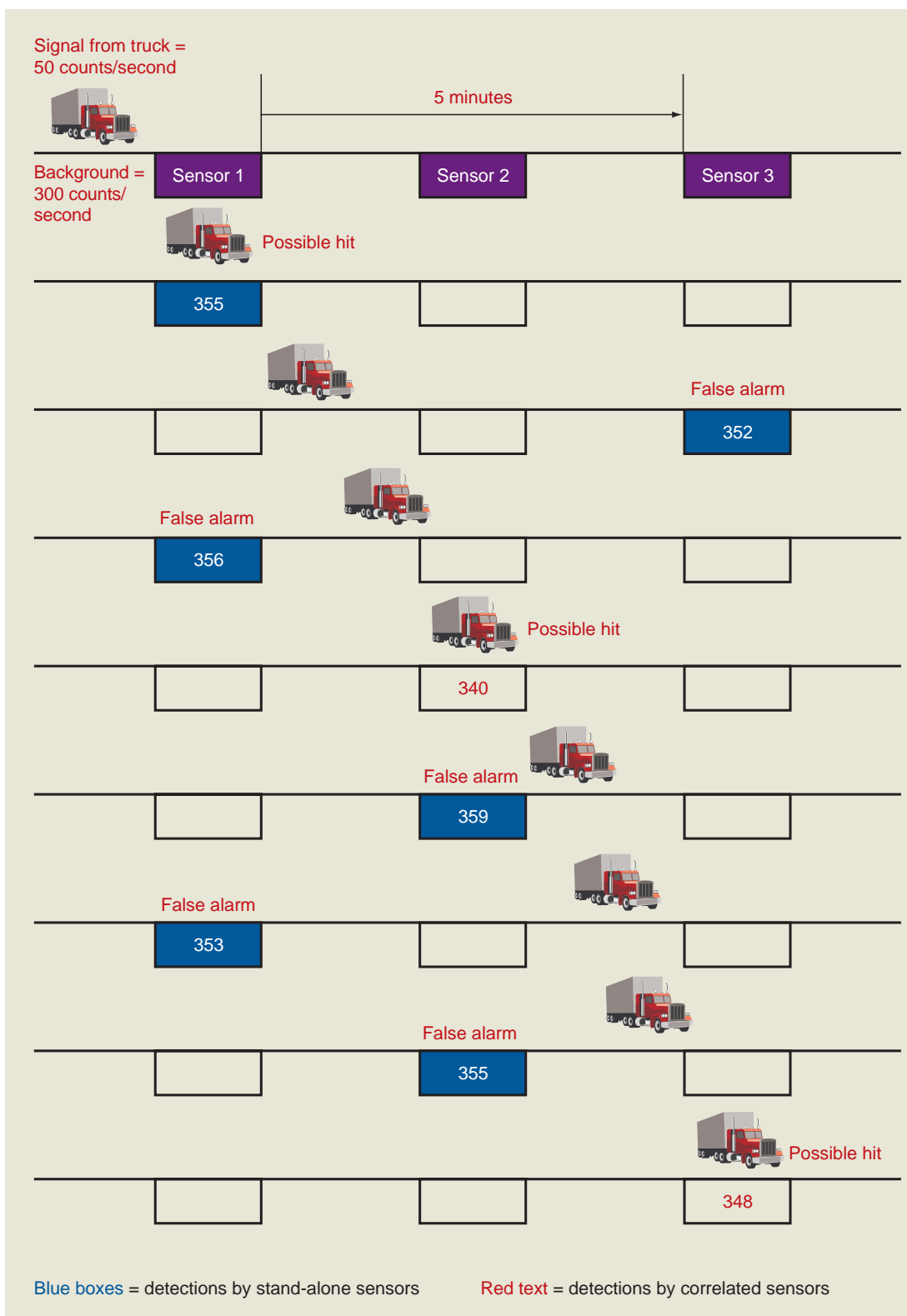
The energy issue, notes engineer Rob Hills, is a big concern for sensors that are networked. “We have a saying that power is everything,” he explains. “Power requirements make a network feasible—or not.” For instance, the Joint Biological Remote Early Warning System (JBREWS) prototype network used 132 commercial sensors, each requiring two batteries (one in the sensor, one in the charger) to operate continuously, for a grand total of nine tons of batteries. To address this problem, the Laboratory developed a communication system that requires an average power of only 1 watt. “And we’re pushing the power requirement down from there,” says Hills.

In a back-to-basics project, Laboratory engineer Dave Harris is researching the underlying physics that is key to creating microsensors for seismic networks. “I believe that Dave’s work—along with our data-fusion techniques—will allow us to create cheap and small sensors, which can be delivered from a remote platform such as unmanned aerial vehicles,” says Hills. Harris has been working with engineer Bruce Henderer, who has developed a prototype sensor about 3 centimeters thick and 6 centimeters square—small enough to hold in the palm of your

hand—and containing a low-power communications device that allows the sensors to network and to configure themselves. “In other words,” says Hills, “once laid down, the sensors would talk to each other and, by determining their neighbors, build a network and paths back to control.” The data processing would take place out in the network, with the network sensors themselves being capable of pattern recognition, information fusion, and decision making.



The prototype sensor being developed at Livermore.



This illustration shows the different results produced by stand-alone sensors versus a correlated sensor network. Here, the sensors are set to register signals of 350 or more counts per second from a truck carrying a signal-emitting device. The stand-alone sensor system simply detects six instances of over-350 signal counts (blue boxes). The networked system, having access to more information, correlates the information to discount all but the first detection as false alarms and to register two others that are under the 350-count threshold as likely "hits," which are then correlated to the first hit.

could do double duty. First, it could provide a way to discard signals that are false alarms. Second, it could pick up on signals that might be real alarms but would have been ignored by stand-alone sensors because the signals were under a preset threshold of sensitivity.

The figure on p. 13 shows how correlated network and stand-alone systems differ. In the figure, the truck carries a device that emits signals averaging 50 counts per second; signals in the natural background are on average 300 counts per second. Three stand-alone sensors are set to register detections, or hits, of 350 or more counts, which would reduce false alarms caused by background variations.

The truck passes the first sensor, which detects 355 counts—a possible hit. It goes on its route and the stand-alone sensors detect five other instances of over 350-count signals. The detections provide no information to the

person at the central command post as to whether they are real alarms or not.

However, if the sensors were networked and able to communicate with each other, a different picture would emerge. “For one thing,” notes Hills, “you can include other information in the system, such as the approximate travel time of the vehicle. A reasonable assumption would be that the vehicle is traveling at the speed limit, because its driver probably would not want to attract attention to himself.”

In the correlated sensor case, the 355-count signal at sensor one is noted as a possible hit. This information is shared with sensor two, and then the system clock starts to track travel time. The travel time between sensors one and three is assumed to be about 5 minutes. Sensor two is on the alert for signals above background that appear within a certain window of time centered on a predetermined time mark,

say, 2.5 minutes. The closer a signal is detected to that 2.5-minute mark, the more weight is given to the probability that the signal is from a real source, rather than some random hiccup from background.

The ensuing signals at sensors one and three are discounted as false alarms because they are uncorrelated, that is, they show no relation to previously recorded data. If the truck is proceeding forward, it would not register at sensor one, which it just passed, and the signal at sensor three comes much too soon. However, the 340 counts detected at sensor two, even though a trifle low, is viewed as a possible hit because it falls within the allotted window of time and is considerably higher than background. This information is passed along to sensor three.

Three signals follow and are discounted as false alarms because of their location and timing. However, the

Bayesian Statistics at Work

While developing the computer algorithms to perform distributed decision making for a sensor network, a team of researchers, including physicist Chris Cunningham, came up with an approach based on Bayesian algorithms. As Cunningham explains it, the Bayesian approach has a couple of pluses. First, it is energy-efficient because communication only occurs when there is a sufficient probability that a target has been detected. Second, each sensor independently extracts features from its raw sensor signals, compares these features with the targets, calculates the likelihood of detection, fuses the likelihoods received from neighboring nodes, and communicates only the new likelihoods to its neighboring nodes. This statistical data fusion can allow each sensor platform to make decisions based on the total information in the network, while reducing the volume of communications among sensors.

The method is based upon the work of an English mathematician, the Reverend Thomas Bayes. Bayes developed a mathematical formula that allows scientists to combine new data with prior conditions. In a sense, it addresses the question,

“Given that an event has occurred that may have been the result of any of two or more causes, what is the probability that the event was the result of a particular cause?” The answer lies not in an absolute yes or no, but in the set of probabilities that the various causes are at play. Bayesian methods allow scientists to combine prior information about a population parameter with information contained in a sample to guide a statistical inference process. A prior probability distribution for a parameter of interest is specified first. Sample information is then obtained and combined through an application of Bayes’s theorem to confirm the prior assumptions. Bayesian methods are used extensively in statistical decision theory.

Livermore’s Wide-Area Tracking System (WATS) is one example of a correlated sensor network that uses algorithms based on Bayesian constructs. In WATS, each sensor computes and exchanges information with its near neighbors in the form of Bayesian probabilities for possible sources. Algorithms reduce the sensor data to probability estimates and then fuse the estimates among the multiple sensors.

348-count signal at sensor three is recorded and its probability of being real is calculated and correlated with the preceding hits.

“What’s happening here is that we’re actually correlating signatures in different domains,” explains Hills. “For this example, we’re correlating data from both temporal and spatial domains: correlating whether the appropriate sensor gets the hit—which is the spatial domain—and whether that hit may be due to the source based on the time of travel between sensors—which is the temporal domain. We then perform some statistical calculations to determine how probable it is that the hit is real, based on the number of counts detected and when—within the allowable window of time—the counts are detected.”

Performing these kinds of calculations for three networked sensors is one thing, but widen a

network to include 100 sensors and it becomes extraordinarily challenging. The computer algorithms needed to track and follow more than one likely pattern and calculate all of the probabilities are extremely complex (see **box on p. 14**) and are only now possible with the increases in computing power.

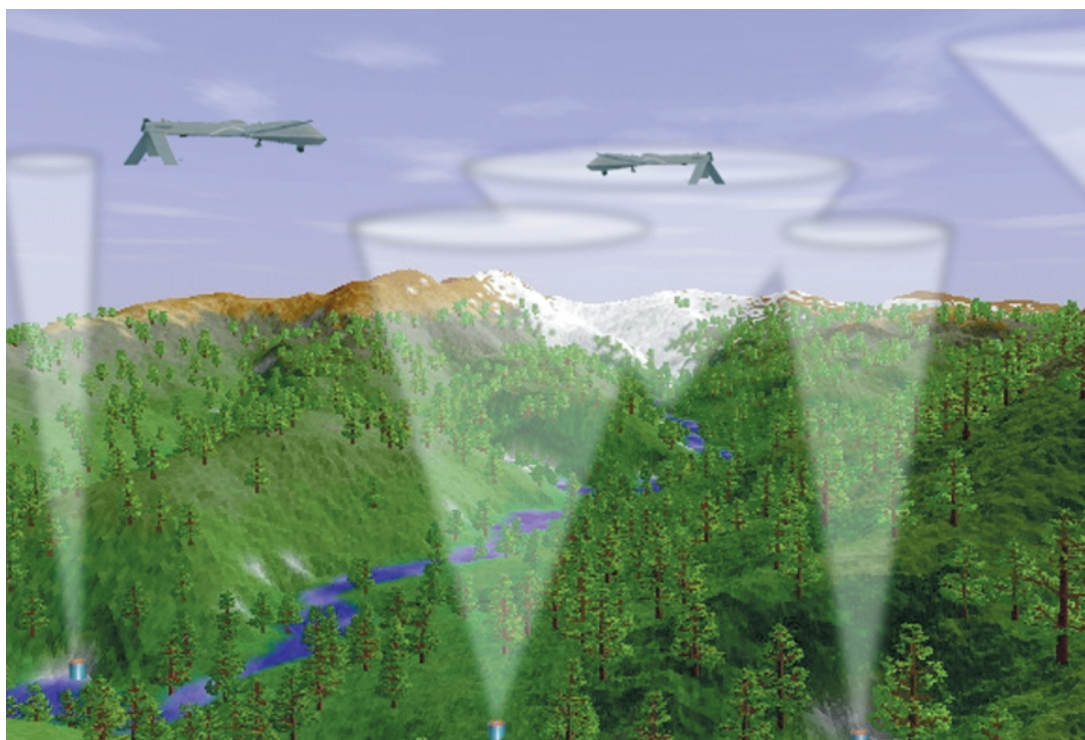
Military and Other Applications

Livermore researchers have been working on many applications of correlated sensor networks. For instance, the Laboratory has developed a prototype correlated sensor network for detecting and tracking a ground-delivered nuclear material. The Wide-Area Tracking System (WATS) is a network of gamma and neutron detectors and communications links, with information continuously evaluated by Laboratory-developed data-fusion algorithms. The sensors

can be permanently deployed at chosen locations or mounted in vans for deployment on demand to protect specific areas for specific situations or events.

The individual sensors share their data with neighboring sensors, process the data, integrate and combine them with other available information (for example, data gathered previously; observed radiation signatures, spectra, and backgrounds; road maps), and finally determine the probability that the signal comes from a real source—all while the system is in the field. In this way, a WATS sensor network can drastically reduce false alarms and detect the entry of a nuclear device or radioactive material into the protected area and track its movement.

The analysis could be performed by a centralized computer at, say, command headquarters, but researchers have found that communications



Researchers at Livermore are exploring the possibility of using unmanned aerial vehicles (UAVs) to place, operate, and maintain sensor networks in rugged terrain. In the figure, the sensors in the network are shown sending their information.

limitations—latencies, available bandwidth, and so on—can be a significant bottleneck for these types of networks. When data are processed in the field, it is necessary to send only bits of information between neighbors, with the final result going to the human user. This type of operation makes the network much more scalable.

Another example of correlated sensor network development involves a recently concluded project called Joint Biological Remote Early Warning System (JBREWS). For JBREWS, the Laboratory was responsible for developing the command, control, communications, computers, and intelligence systems for a network of biodetectors that could provide U.S. field troops with early warning of a biological attack. Although the project is not continuing, it has allowed the Laboratory to make important progress in developing data-fusion solutions that could be applied to any type of correlated sensor network. The communications paradigms that were developed in JBREWS let Laboratory researchers take a big step toward solving one part of the data-fusion problem—that is, how to quickly and automatically establish a communications fabric for data fusion to work within.

In this communications scheme, the array of sensors forms an automatically reconfiguring, or self-healing, network, as follows. Once the sensors are in place, they communicate with each other via radio frequencies so each sensor can map where its neighboring sensors are. The sensors then radio-test each other and develop an efficient communications path back to the central command post. If, for example, one sensor can't communicate directly with the command post on the other side of a hill, it passes its data to its neighbors, to be relayed with the neighbors' data to other units, and so on, until the information reaches its destination. If a

unit is knocked out by a malfunction or hostile action, its communication relay functions are picked up by surrounding units and a secondary path is formed. In short, the system quickly recognizes and adjusts to the absence of any sensor units. A big plus for this type of network and others like it, Hills notes, is that there are no single-point failures.

Another military application would connect these sensor networks with other systems, such as the Laboratory-developed Counterproliferation Analysis and Planning System (CAPS). CAPS can model the various processes (chemical, biological, metallurgical) used by proliferators to build weapons of mass destruction and their delivery systems. CAPS helps users identify critical processing steps or production facilities that, if disabled or destroyed, would prevent that country from producing weapons of mass destruction. "Now imagine adding correlated sensor networks to the mix," says Hills. "Sensors on the ground and in the air could track processes in real time. A user could click on the Web-based CAPS page and find out what's going on right then at such-and-such a facility."

Yet another application for such networks is in tactical engagement systems. With sensor networks as part of these systems, a soldier would never be alone in the field. The sensor network could supply information not just to people in the field, but to those who are out of harm's way as well. They would all be tied together in a collaborative environment. With such a system, the electronic network would be displayed in a chest-top system so that a soldier could "see" the environment and watch his back—all from one small device.

Correlated sensor networks could also be used in nonmilitary applications to provide temporary communication infrastructures after a destructive

earthquake or to provide information during large firestorms. For example, there are microclimates within a large fire. A correlated sensor network could track temperatures, humidity, and wind in three dimensions, providing valuable information to firefighters.

David McCallen, director for Livermore's Engineering Center for Complex Distributed Systems, notes that current research to develop self-healing, self-configuring networks of seismic sensors would be useful in studying how large structures respond in earthquakes. "Once these networks are developed, it's a small step to apply them to large structures, such as bridges, to gather data on how these structures vibrate and respond under various circumstances," he explains. "When you consider that to densely instrument a structure like the Golden Gate Bridge takes hundreds of sensors, having a system that's wireless and self-configuring is very attractive." He adds that the California Department of Transportation is also interested in using such networks to monitor steep hillsides for possible landslides.

Putting Sensors in Their Place

One of the challenges to using these networks is getting them in place, in real terrain. "In a battlefield scenario, for instance, or during a wildfire, you can't have people tromping in to set down sensors," says Hills. One answer is to use unmanned aerial vehicles (UAVs), such as the U.S. Air Force's Predator or even smaller, 2-meter-wingspan UAVs. In one project, researchers are evaluating the use of UAVs to rapidly place, operate, and maintain sensor networks in rugged terrain. Such vehicles could drop the sensors in predetermined locations and then act as airborne routers. Once in place, the sensors would form a network, communicate with each other,

and send information skyward to be collected and transmitted by the planes.

Using Laboratory-designed software, researchers could create self-configuring and self-healing networks made up of small, low-power sensors. If the sensors are cheap enough, the result is a ready-to-use network—a wireless “network on demand.” In this kind of setup, the UAVs become part of the system, sharing information about locations of all the sensors and other UAVs, sensor data requirements, connectivity maps, and UAV-sensor assignments; leveling the workload; and backing each other up in case one or another UAV is put out of commission. “This is just one of the directions in which we’re moving to position ourselves for the future,” says Hills.

Looking toward the Future

The idea of correlated sensor networks is not Livermore’s alone. Other organizations and commercial companies

are exploring applications and, like the Laboratory, pushing on what’s possible in the laboratory to get to what’s feasible in the field. “The key,” says Hills, “is to find ways of gathering all those data together and turning them into usable, real-time information to let the user make decisions. Here at the Laboratory, we’ve got the key in hand and are turning it in the lock. It’s only a matter of time before the door opens.”

—Ann Parker

Key Words: Bayesian statistics, correlated sensor networks, Counterproliferation Analysis and Planning System (CAPS), gamma detector, Joint Biological Remote Early Warning System (JBREWS), neutron detector, nuclear terrorism, seismic detector, sensor or network fabrics, tactical engagement systems, unmanned aerial vehicle (UAV), Wide-Area Tracking System (WATS).

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About the Scientist



ROB HILLS is the acting associate division leader for the Tactical Systems Section in the Nonproliferation, Arms Control, and International Security Directorate. He leads a variety of projects that include research and development for sensors and sensor networks, military systems analysis, and computer-based battlefield conflict simulation models. Hills received a B.S. in electrical engineering from the Michigan Technological University in 1983. He joined

Livermore in 1988 to perform research that involved automating the transfer of existing digital designs to new implementation technologies. Thereafter, he participated in several projects to develop sensor systems and image-processing technologies for astronomical telescopes. For example, he was a member of the team that developed the camera system to detect dark matter; the system won an R&D 100 Award for being one of the most technologically significant new products in 1993. Hills has led research and development efforts for microtechnology tools, such as a polymerase chain reaction system, used both in medical and national security applications. And he has engineered optical interconnects for parallel computer systems as well as overall architectures for self-configuring and self-healing communications networks.

It's the Pits in the Weapons Stockpile

WITH no replacements being built for them, the nuclear weapons in the stockpile are sitting there, steadily aging. Materials inside them may be developing minor sags and wrinkles, just as we humans do over time. In the mid-1990s, in the first years after nuclear testing stopped, the Department of Energy established an Enhanced Surveillance Campaign to determine whether those sags and wrinkles were indeed developing and, if so, whether they would affect the safety and ultimate performance of the weapons.

The Enhanced Surveillance Campaign is a part of the Stockpile Stewardship Program managed by DOE's National Nuclear Security Administration (NNSA). The detection and prediction of changes in an aging stockpile are among the most challenging and technically engaging aspects of stockpile stewardship. In the effort to understand stockpile aging, the Livermore and Los Alamos national laboratories joined forces with two NNSA plants, Pantex and Kansas City, to examine

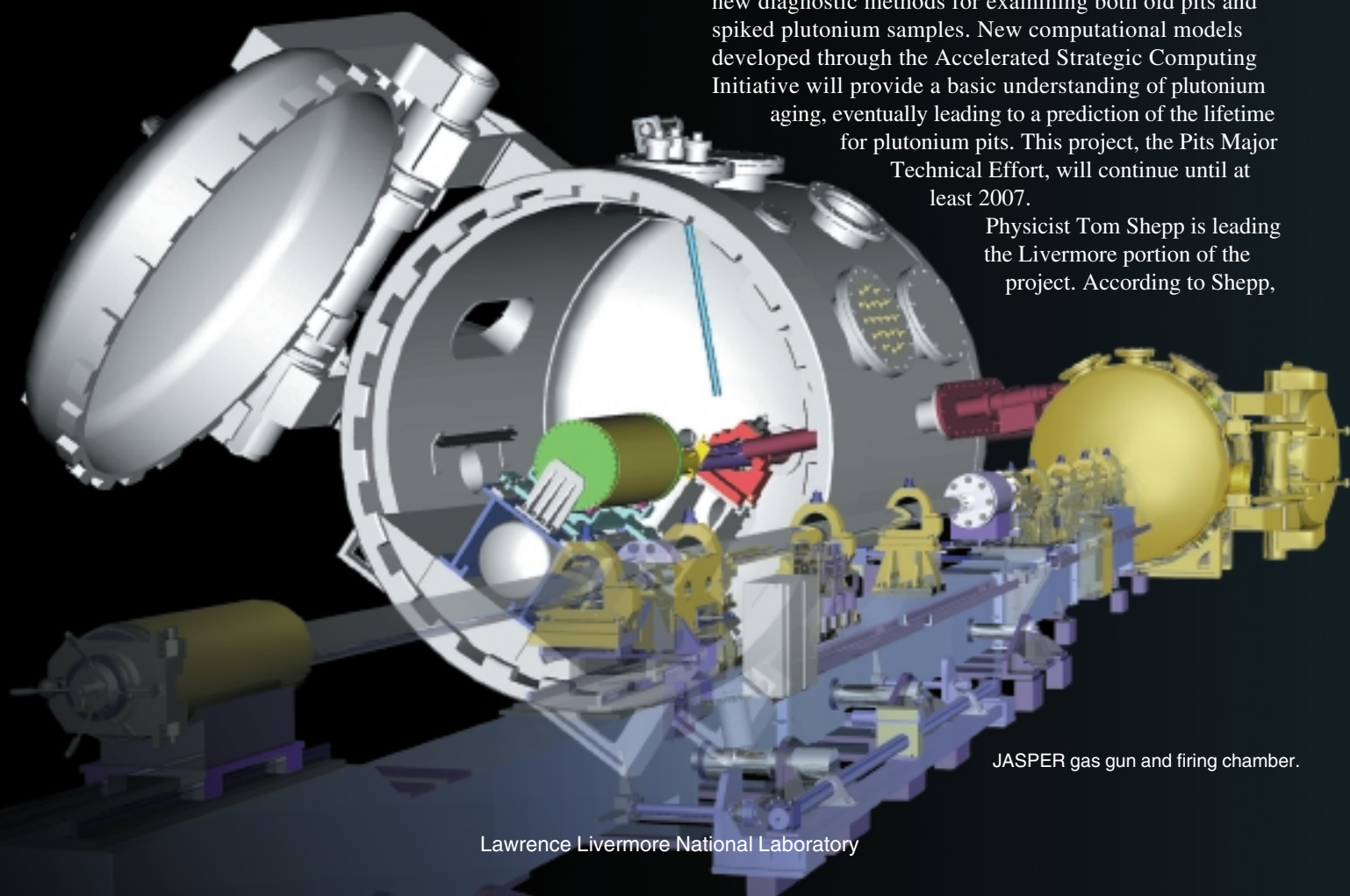
the pits inside nuclear weapons. The pits are shells of plutonium that play a key role in the performance of a nuclear weapon. The energy released when the plutonium atoms fission, or split, helps to start the huge fusion explosion of a modern thermonuclear weapon. Knowing how the pit changes as it ages is critical to predicting the performance of weapons in the stockpile.

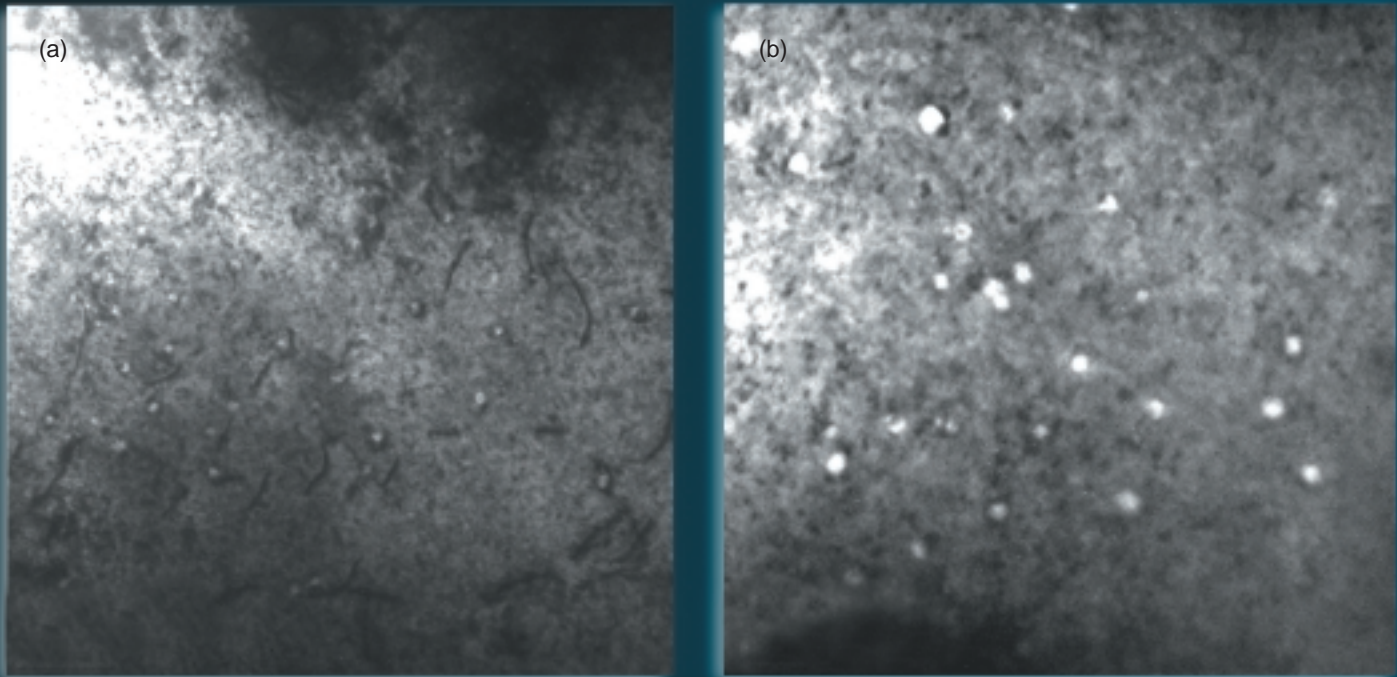
Most pits in the U.S. stockpile are now 10 to 20 years old. NNSA wants to be able to project their lifetime to 60 years so decision makers will know what to expect as the pits age and whether they will still be safe and reliable. In response to that challenge, Livermore and Los Alamos scientists developed a way to spike weapons-grade plutonium to prompt it to age as much as 16 times faster than normal. At the same time, some of the oldest pits in the stockpile are being examined to establish a baseline against which the accelerated aging samples can be measured. Researchers are also developing new diagnostic methods for examining both old pits and spiked plutonium samples. New computational models developed through the Accelerated Strategic Computing Initiative will provide a basic understanding of plutonium aging, eventually leading to a prediction of the lifetime for plutonium pits. This project, the Pits Major Technical Effort, will continue until at least 2007.

Physicist Tom Shepp is leading the Livermore portion of the project. According to Shepp,

Lawrence Livermore National Laboratory

JASPER gas gun and firing chamber.





Samples of plutonium from the stockpile were subjected to isochronal annealing to induce the growth of voids. This sample was annealed at 400°C for one hour. (a) A look at 400 nanometers of material. (b) A closer view of just 200 nanometers of plutonium, in which minute voids are clearly visible.

“We are working to protect the health of the stockpile by providing advance warning of manufacturing and aging defects. NNSA especially wants to know whether they will need to build a facility for manufacturing new pits.” NNSA’s former pit production plant at Rocky Flats has been closed for many years, and reopening it is not an option. If pits are aging unacceptably, they will have to be replaced, necessitating construction of a modern manufacturing plant.

The Aging Process Up Close

Plutonium experts have two major concerns about aged plutonium: corrosion reactions and the results of self-irradiation. Most Livermore research is concerned with self-irradiation. When plutonium decays spontaneously, it emits an alpha particle (a helium nucleus) to become uranium. The heavy uranium atom recoils, displacing other plutonium atoms and disrupting the surrounding microstructure.

Says Shepp, “Spontaneous decay creates a cascade of chaos. We know that most of the helium atoms return to their old homes, but some don’t, leaving microscopic voids behind. When they find new homes, they cause the pit to swell ever so slightly and may change the dynamic mechanical properties of the pit material. Over time, changes in the density, shape, and mechanical properties of the pit may affect the overall performance of the weapon.”

Two machines at Livermore have been particularly useful for examining plutonium samples from the stockpile for material

changes that result from self-irradiation. One is the new 300-kiloelectronvolt field-emission transmission electron microscope (TEM), the best one in the DOE complex. The new TEM is providing a better understanding of the microstructural evolution and stability of plutonium as a function of age and deformation. The other machine is the three-dimensional positron microprobe, which has the highest spatial resolution of any positron analysis system in the world. Positron annihilation lifetime spectroscopy can detect the size, location, and concentration of possible voids in naturally aged plutonium. (See *S&TR*, March 2001, pp. 23–25, and December 1998, pp. 13–17.)

Experiments by Livermore scientists on the Los Alamos gas gun as well as nonnuclear tests of plutonium at the Nevada Test Site are supplying more data points for the dynamic properties of stockpile pits. These measurements help assess how aging affects mechanical properties, including the equation of state, dynamic tensile fracture (spall), work hardening, yield strength, and generation of defect structures.

In another set of experiments, plutonium is cooled to near absolute zero and then cycled to higher and higher temperatures in a process known as isochronal annealing. The process damages plutonium and provides scientists with a fundamental understanding of the behavior of damaged plutonium.

These data come together to create more accurate models that can predict aging effects, overall performance, and the safety of pits and the weapons that contain them. Livermore

has produced the first simulations of the quantum molecular dynamics of plutonium to study what is happening to individual atoms over very brief time periods. At the other end of the time spectrum, Monte Carlo statistical analyses examine a representative selection of the millions of interacting atoms and their daughter particles over the long-term processes of void creation and resulting swelling.

A Time Machine for Plutonium

These same experiments will also be performed on spiked plutonium alloys. If typical weapons-grade plutonium, plutonium-239, is spiked with some plutonium-238, which decays more quickly, the self-irradiation process dramatically picks up speed. If 5 percent of the plutonium-239 is replaced with plutonium-238, the sample will age 11 times faster than normal plutonium-239. Aging can be accelerated by a factor of 16 over normal aging processes if 7.5 percent of the sample is plutonium-238. A useful measure of acceleration aging is defined as the number of years required to reach a radiation dose that results in 10 displacements per atom. Weapons-grade plutonium normally takes 100 years to reach this dose but will need just 6.25 years if it is spiked with 5-percent plutonium-238.

The first batch of 7.5-percent-spiked plutonium was created in May 2000 at Livermore's Plutonium Facility (see *S&TR*, March 2001, pp. 4–12). In 2004, researchers will begin to study batches of spiked plutonium that have “aged” 60 years, the lifetime NNSA hopes to achieve. In fact, this accelerated aging process will allow studies of samples that have aged well beyond the ages of the oldest plutonium pits in the stockpile.

New Diagnostics and More Information

Over the next few years, several new diagnostic tools will be deployed at Livermore, Los Alamos, and the Pantex Plant.

To better understand damage to plutonium weapon pits, Livermore scientists integrate modeling, theory, and experimentation. In this example, experiments with the positron microprobe supply data for better models of defects at various time scales, which leads to improved theory about how best to use positrons to predict defects. Better theory in turn makes for better experiments and thus better models, in a virtually endless loop.

They include a high-resolution computed tomography system that Livermore is enhancing for use at the Pantex Plant. Livermore is further developing laser-shock diagnostics for pit surveillance. And its JASPER (for Joint Actinide Shock Physics Experimental Research) gas gun will come on line at the Nevada Test Site in about a year for shock tests of plutonium.

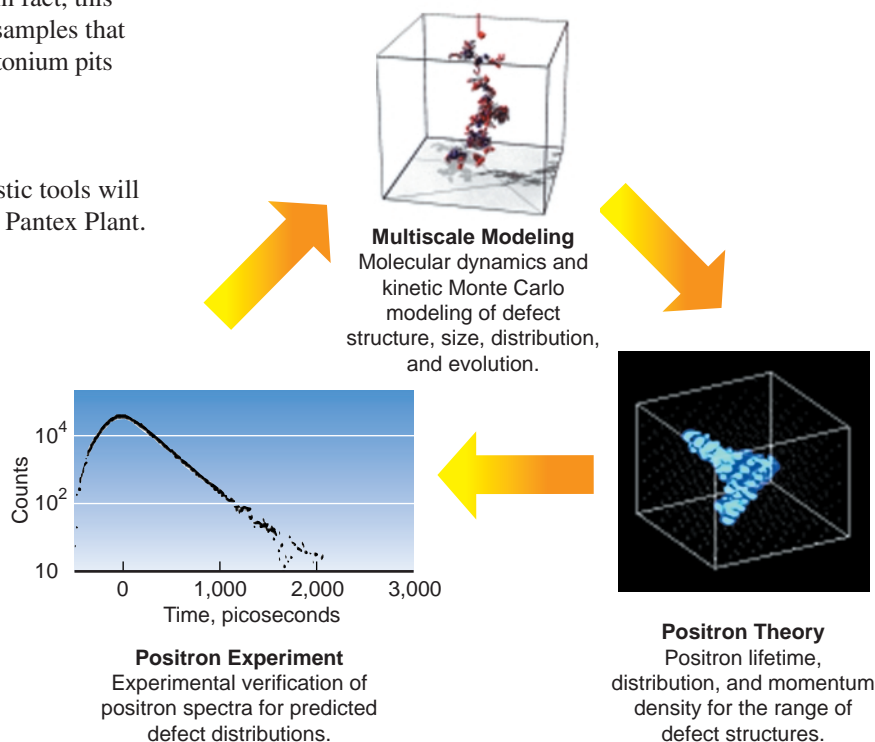
Shepp says, “During the first years of the project, we were getting ready by preparing the spiked alloys and starting the baselining process. Now we’re beginning to see results.” During the upcoming year, the team will validate the accelerated aging methodology by measuring aged samples against pit samples of comparable age from the stockpile. At the same time, Livermore and Los Alamos will finish characterizing the oldest pit materials of the most common pit type.

All studies to date indicate that the U.S. nuclear arsenal is robust and shows few effects of aging. Identifying the time scales of plutonium deterioration is critical for maintaining the continued safety and reliability of the stockpile.

—Katie Walter

Key Words: Enhanced Surveillance Campaign, nuclear weapons, pits, plutonium.

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Looking into the Shadow World

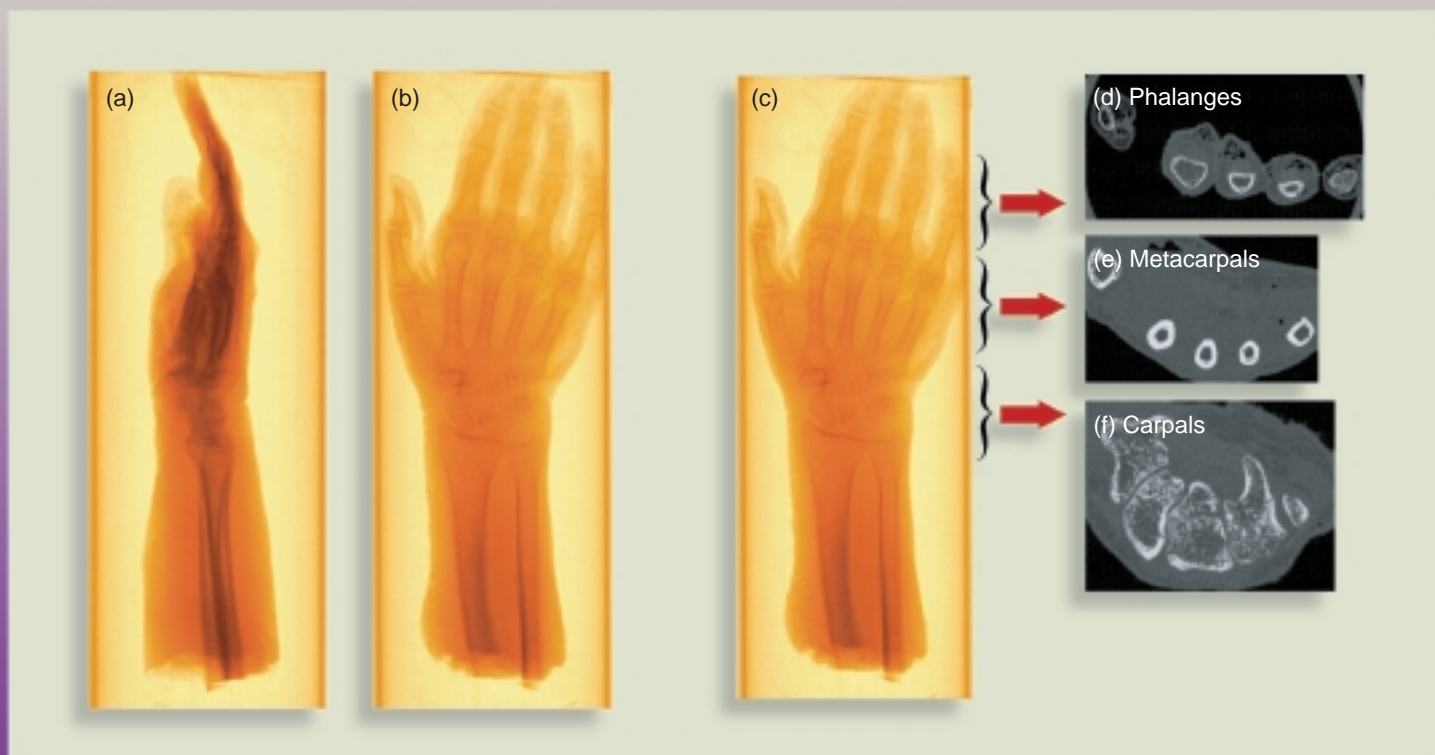
THE x-ray image of your daughter's broken arm is really a picture of shadows. If the image is caught on film, dense material like bone will appear lighter because it absorbs more of the x rays than organs or soft tissue. The x ray, or radiograph, easily reveals the broken bone, showing where it needs to be reset.

To obtain the image, the technician places your daughter's arm between the radiation source (x-ray machine) and a detector, which may be film or a digital device. The end result is that three dimensions are compressed to produce a two-dimensional image of your daughter's arm. There will be a bit of blur, but the image meets the doctor's needs just fine.

Computed tomography (CT) takes the radiography process several steps further. A tomograph, whether made for a medical, industrial, or scientific application, starts out as radiographic views—as many as 1,000 of them—taken around a given plane. The measurements in those two-dimensional

radiographic projections are mathematically reconstructed into a three-dimensional volume of data. When the reconstruction is complete, doctors or researchers can view individual cross-sectional planes of the object with all other planes eliminated.

Medical radiographs and tomographs are concerned with contrast—the degree of difference between dark and light in images—as well as the shape and location of bone, internal organs, tumors, and so on. But many industrial applications and the National Nuclear Security Administration's Stockpile Stewardship Program—to preserve the reliability and safety of nuclear weapons—require more than contrast and geometry. Many stockpile stewardship applications require reconstructed tomographs that researchers can use to determine the density of an object and accurately identify minute voids and other changes. The data produced by current radiographic methods and tomographic reconstruction techniques have just not been good enough to meet such requirements.



(a), (b) Radiographs of a woman's hand. Because radiographs compress three dimensions into two, in (a) it is possible that the woman has just two fingers and not five. But (b) shows that she indeed has five fingers, although it provides no information on her hand's internal workings. (c) One of many radiographs taken of the same hand as part of a tomographic scan. (d), (e), and (f) Cross-sectional images of the hand that are only possible with three-dimensional computed tomography.

For useful tomographic reconstructions, researchers must be able to model and simulate the radiography process to provide good data for the reconstructions. Right now, researchers can simulate two-dimensional radiographs for Livermore applications to about a 10-percent accuracy. Future applications will require an accuracy of about 1 percent, that is, differences in image contrast as small as 1 percent should be perceptible. Tomographic reconstruction is also problematic. The best reconstruction software available today cannot calculate the blurring effects caused by the detector and the radiation source; the software accounts for blurring after the fact, through a deconvolution process. X rays come in a spectrum of energies that attenuate differently in different materials, but current reconstruction methods ignore the differences. Noise, artifacts from x-ray scatter, and the spectrum of x rays from the source further diminish tomographic results. With current limitations, the accuracy of computed tomography is typically about 15 percent.

To attain 1-percent accuracy, Livermore's Center for Nondestructive Characterization set up a team headed by physicist Harry Martz to achieve that goal. The team's first order of business was to improve the radiographic imaging process to get the best data possible for tomographic

reconstructions. Martz and team members improved the data acquisition system of Livermore's 9-megaelectronvolt linear accelerator, changing it to better account for radiation scattering and blur from the radiation source. Equally important, they modeled the detector using a Monte Carlo code so they would understand detector response and be able to reduce or eliminate blur caused by the detector.

Then they began to develop software that incorporates the real effects of blur, attenuation differences, noise, and artifacts at the front end of a reconstruction to achieve the tomographic accuracy that Livermore needs.

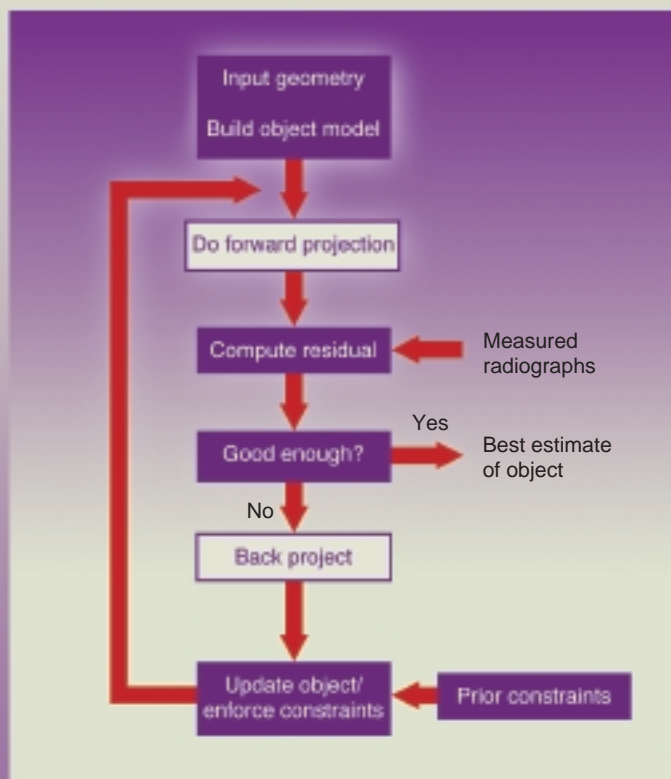
Challenges for Software

"Even with a pure material, we cannot get a perfect radiograph or tomographic reconstruction," says Martz. "So it is hardly surprising that we cannot get high-quality reconstructions of objects made of several different kinds of materials."

One challenge is that for some tomographic reconstructions, only a limited amount of data is available, sometimes as few as 4 to 20 radiographic views. "The manner in which we do tomographic reconstruction is different with a smaller number of views," says Morry Aufderheide, creator of HADES, a ray-tracing code for simulating the radiographic projections. Martz, Aufderheide, and the rest of the team members are working on coupling HADES with an optimization algorithm to perform tomographic reconstruction with a limited number of radiographic views.

Aufderheide named HADES for the Greek underworld, where the dead were sometimes referred to as shadows. HADES can accurately simulate the radiographic process—from radiation source to image formation and detection. With the recent huge increase in computing power, HADES can include radiographic physics—blur from both the detector and the radiation source, differing energy attenuations, and noise—in its calculations. HADES incorporates detailed models of various radiation sources and detectors to understand blur, noise, and scattering.

HADES can also operate with an optimization algorithm known as constrained conjugate gradient (CCG), developed by Livermore engineer Dennis Goodman several years ago. CCG has been used for adaptive optics systems on large



Flowchart of the HADES-CCG tomographic reconstruction process. Items with a purple background are operations that CCG performs. Items with a gray background are operations that HADES performs. All results are passed between the codes using shared files.

telescopes and was first applied to tomographic reconstruction a few years ago. Goodman took a standard conjugate gradient code and modified it so that a researcher can specify constraints. For example, in a tomographic reconstruction, totally opaque portions of an object can be ignored. The code also performs well with limited data sets.

Reconstructing a CT image entails solving a large matrix equation that relates simulations of the object being reconstructed to the many radiographic projections taken of it. First, CCG creates a model of the object, which may be based on some known data or may simply be all zeros. HADES then simulates a radiograph of this modeled object. The CCG search algorithm compares the simulated radiograph to an actual measured radiographic projection, seeking what is known as a maximum likelihood solution. This search continues iteratively, efficiently modifying the model using conjugate gradients and user-specified constraints, until the difference between the actual measured radiographs and the simulated or calculated radiographs is satisfactorily small. This reconstruction technique also minimizes, but does not eliminate, the possibility of introducing spurious features.

CCG and HADES are both complex codes, created and maintained separately. Attempting to actually merge the two codes would be time-consuming and inefficient. Merging them could also make maintenance and upgrades to either code more difficult. The most effective solution so far has been to run them in parallel and exchange information between them in shared files.

Experiments Validate Codes

Martz and his team have performed several experiments to test their new capability in experimental and simulation radiography as well as the new CT image reconstruction technique. They used a variety of test objects because each one tests a different aspect of the simulation and tomographic reconstruction process.

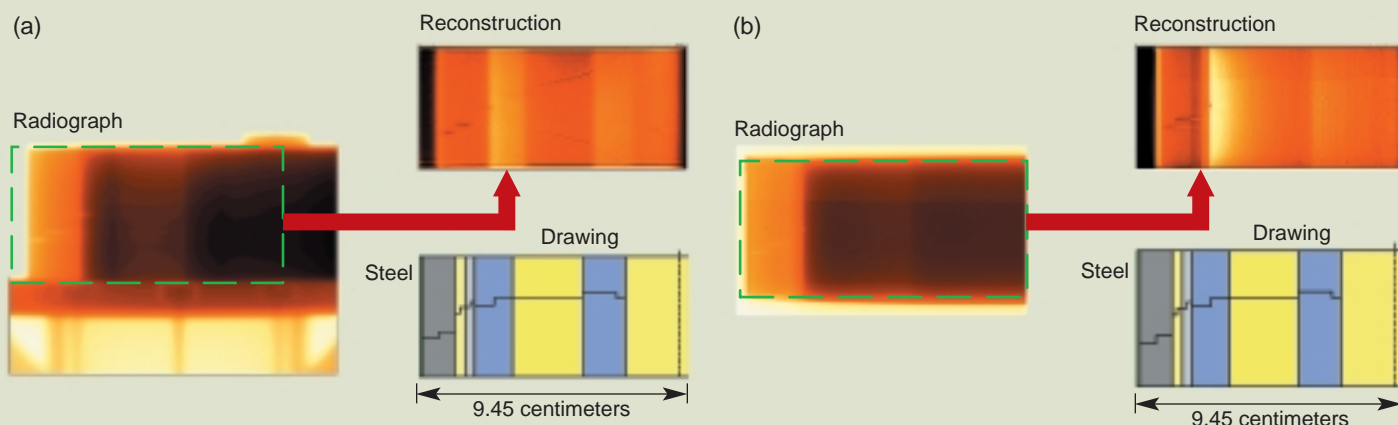
In one experiment, they imaged two copper step wedges to quantify their improvements to the radiography experimental and simulation process.

The experiment showed that new collimators have indeed reduced scattering at the detector. It also showed a better agreement with simulations by accounting for the response of the digital amorphous-silicon detector, which they had modeled with a Monte Carlo code and incorporated into HADES. Of the experiments with these test objects, fabricated of a single pure material, a pleased Martz says, "We got between 1- and 2-percent radiographic accuracy."

Continuing the evaluation of the new radiography modeling process, the team tested a more complicated object, a disk made of eight layers of five different materials. The first experiment used neutron radiography (see *S&TR*, May 2001, pp. 4–13) and was performed at the Ohio University Accelerator Laboratory, one of the few neutron sources in the country. The team took 64 radiographic images of the disk. One radiographic image and a two-dimensional reconstruction of its radiographic projection are shown in the **top figure on p. 24**. The quality of the reconstruction is remarkable, considering that it was made with just one rather than all or even several of the 64 images.

Top view of eight-layer test object.





(a) Reconstruction of eight-layer test object with neutrons and (b) reconstruction of eight-layer test object with x rays.

When few projections are available, the quality of the input data must be as high as possible. The high quality of the CT reconstruction is also a measure of the effectiveness of the HADES-CCG reconstruction process.

When the same disk was tested using Livermore's 9-megaelectronvolt x-ray source, the results were quite different, as shown in the figure above. The x rays could not penetrate as far as the neutrons, just to the fourth or fifth layer of the disk, producing only noise beneath those layers. However, in the layers they did penetrate, the x rays provided better contrast than neutron imaging. Neutron and x-ray imaging complement each other to provide more complete tomographic reconstructions.

The team has just begun working on full three-dimensional tomographic reconstructions of objects made from multiple materials. This most complex version of the tomographic process is what Livermore really needs for stockpile stewardship and other projects. It's a long way from the radiograph of your daughter's arm.

—Katie Walter

Key Words: computed tomography, constrained conjugated gradient (CCG), HADES, radiographic modeling, radiography, Stockpile Stewardship Program.

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(continued from p. 2)

Distant stars individually imaged by Hubble

At the June meeting of the American Astronomical Society in Pasadena, California, Michael Gregg of the Institute of Geophysics and Planetary Physics at Livermore and the University of California at Davis presented some exciting images of stars. They were pictures he had taken of individual stars in a galaxy called NGC3379, located about 30 million light years from Earth. The pictures resulted from a collaboration in which Gregg, colleagues from the Space Telescope Science Institute, the Universidad Catolica de Chile, and the University of Hertfordshire, England, used the Hubble Space Telescope's near-infrared camera and multiple-object spectrograph to capture images.

Infrared images help astronomers determine star composition and formation. This knowledge allows them to compare the galaxy in which the stars are found with the Milky Way and other nearby galaxies.

Gregg's star pictures, the first instance of individual stars being resolved in infrared at such great distance, also show that the NGC3379 contains variable stars, which change in brightness over time. Some of them were no longer visible in images taken three months later. Because NGC3379 is an elliptical galaxy, one that is thought to contain few variable stars, Gregg said that current assumptions about elliptical galaxy evolution may need to be revised.

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Advanced communications links in free space

The Defense Advanced Research Projects Agency (DARPA), a principal research and development organization for the Department of Defense, has funded the first phase of a project to develop powerful new capabilities for free-space communications, such as data transmission from Earth stations to satellites. Called Coherent Communications, Imaging, and Targeting (CCIT), the project would enable secure communications at speeds of several gigabits over ranges greater than 1,000 kilometers. And the transmitted three-dimensional images would be aberration-free.

Livermore is the lead organization for the \$9.5-million Phase I work, which will be performed over two years. The team includes researchers from academic institutions and companies in microelectromechanical systems (MEMS), photonics, and aerospace. The team is responsible for modeling; coordinating MEMS development; integrating MEMS, photonics, and high-speed electronics into a prototype system; and demonstrating the concept. DARPA expects that the innovations and integrations achieved by this work will provide systems useful late into this century.

Says Eddy Stappaerts, the CCIT program manager at Livermore, "The CCIT program has the potential to be a major development in secure, free-space communications for a range of military applications as well as having a significant impact in the commercial arena."

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Each month in this space we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Pressure Enhanced Penetration with Shaped Charge Perforators

Lewis A. Glenn

U.S. Patent No. 6,223,656 B1

May 1, 2001

A downhole tool, adapted to retain a shaped charge surrounded by a super, atmospherically pressurized light gas, is employed in a method for perforating a casing and penetrating reservoir rock around a wellbore. Penetration of a shaped-charge jet can be enhanced by at least 40 percent by imploding a liner in the high-pressure, light-gas atmosphere. The gas pressure helps confine the jet on the axis of penetration in the later stages of formation. The light gas, such as helium or hydrogen, is employed to keep the gas density low enough so as not to inhibit liner collapse.

System and Method for Optically Locating Microchannel Positions

Laurence R. Brewer, Joseph Kimbrough, Joseph Balch, J. Courtney Davidson

U.S. Patent No. 6,225,635 B1

May 1, 2001

A system and method is disclosed for optically locating a microchannel position. A laser source generates a primary laser beam that is directed at a microchannel plate, whose microchannels are variously located. A back-reflectance beam detector receives a back-reflected beam from the plate, generated when the primary laser beam reflects off the plate. When the back-reflected beam exceeds a predetermined threshold, which indicates the presence of a microchannel, a photodiode circuit generates a trigger signal. The method of this invention includes the steps of generating a primary beam and generating a trigger signal in the presence of a microchannel.

Reflective Optical Imaging Systems with Balanced Distortion

Russell M. Hudyma

U.S. Patent No. 6,226,346 B1

May 1, 2001

Optical systems compatible with extreme ultraviolet radiation, comprising four reflective elements for projecting a mask image onto a substrate, are described. The four optical elements are, in order from object to image, convex, concave, convex, and concave mirrors. The optical systems are particularly suited for step and scan lithography methods. The invention enables the use of larger slit dimensions associated with ring-field scanning optics, improves wafer throughput, and allows higher semiconductor device density. The inventive optical systems are characterized by reduced dynamic distortion because the static distortion is balanced across the slit width.

MoRu/Be Multilayers for Extreme Ultraviolet Applications

Sasa C. Bajt, Mark A. Wall

U.S. Patent No. 6,228,512 B1

May 8, 2001

High-reflectance, low-intrinsic-roughness, and low-stress multilayer systems for extreme ultraviolet (EUV) lithography consist of amorphous molybdenum ruthenium (MoRu) and crystalline beryllium (Be) layers. Reflectance greater than 70 percent has been demonstrated for MoRu/Be multilayers with 50 bilayer pairs. Optical throughput of MoRu/Be multilayers can be 30 to 40 percent higher than that of Mo/Be multilayer coatings. The throughput can be improved using a diffusion barrier to make sharper interfaces. A capping layer on the top surface of the multilayer improves the long-term reflectance and EUV radiation stability of the multilayer by forming a very thin native oxide that is water resistant.

Paper Area Density Measurement from Forward Transmitted Scattered Light

Jackson C. Koo

U.S. Patent No. 6,229,612 B1

May 8, 2001

A method whereby the average paper fiber area density (weight per unit area) can be directly calculated from the intensity of transmitted, scattered light at two different wavelengths, one being a nonabsorption wavelength. The method also makes it possible to derive the water percentage per fiber area density from a two-wavelength measurement. In an example of this measurement technique, the optical transmitted intensity at a 2.1-micrometer cellulose absorption line is measured and compared with another scattered, optical transmitted intensity from a nearby spectrum region, such as 1.68 micrometers, where there is no absorption. From the ratio of these two intensities, one can calculate the scattering absorption coefficient at 2.1 micrometers. The absorption coefficient at this wavelength is then experimentally correlated to the paper fiber area density.

High Reflectance and Low Stress Mo₂C/Be Multilayers

Sasa Bajt, Troy W. Barbee, Jr.

U.S. Patent No. 6,229,652 B1

May 8, 2001

A material for extreme ultraviolet (EUV) multilayers that will reflect at about 11.3 nanometers, have a high reflectance, low stress, and high thermal and radiation stability. The material consists of alternating layers of molybdenum carbide (Mo₂C) and beryllium (Be) deposited by direct current magnetron sputtering on a substrate such as silicon. In one example, a Mo₂C/Be multilayer gave 65.2 percent reflectance at 11.25 nanometers measured at 5 degrees off normal incidence angle; it consisted of 70 bilayers with a deposition period of 5.78 nanometers and was deposited at 0.83 millitorr argon (Ar) sputtering pressure, with the first and last layers being Be. The

stress of the multilayer is tensile and only +88 megapascals, compared with +330 megapascals for Mo/Be multilayers of the same thickness. The Mo₂C/Be multilayer was capped with carbon that produced an increase in reflectivity of about 7 percent over a similar multilayer with no carbon-capping material, thus raising the reflectivity from 58.3 percent to over 65 percent. The multilayers were formed using either Mo₂C or Be as the first and last layers. Initial testing has shown the formation of beryllium carbide at the interfaces between the layers, which both stabilizes and has a smoothing effect, and appears to be smoother than the interfaces in Mo/Be multilayers.

Micromachined Low Frequency Rocking Accelerometer with Capacitive Pickoff

Abraham P. Lee, Jonathan N. Simon, Charles F. McConaghy

U.S. Patent No. 6,230,566 B1

May 15, 2001

A microelectromechanical sensor that uses capacitive readout electronics. The sensor involves a micromachined, low-frequency rocking accelerometer with capacitive pickoff fabricated by deep reactive ion etching. The accelerometer includes a central silicon proof mass, is suspended by a thin polysilicon tether, and has a moving electrode (capacitor plate or interdigitated fingers) located at each end of the proof mass. During movement (acceleration), the tethered mass moves relative to the surrounding packaging. This deflection is measured by a plate capacitor or interdigitated finger capacitor, with the cooperating fixed electrode (capacitor plate or interdigitated fingers) positioned on the packaging, for example. The micromachined rocking accelerometer has a low frequency (less than 500 hertz), high sensitivity (microgauss), and uses minimal power. The capacitors are connected to a power supply (battery) and to sensor interface electronics, which may include an analog-to-digital converter, logic, radiofrequency communication link, and antenna. The sensor (accelerometer) may be packaged along with the interface electronics and a communication system in a 5- by 5- by 5-centimeter cube. The proof mass may be asymmetric or symmetric. Additional actuating capacitive plates may be used for feedback control, which gives a greater dynamic range.

Microwave Hematoma Detector

Waleed S. Haddad, James E. Trebes, Dennis L. Matthews

U.S. Patent No. 6,233,479 B1

May 15, 2001

The microwave hematoma detector is a noninvasive device used to detect and localize blood pooling and clots near the outer surface of the body. Although geared toward finding subdural and epidural hematomas, the device can be used to detect blood pooling anywhere near the surface of the body. Modified versions of the device can also detect pneumothorax, organ hemorrhage, and atherosclerotic plaque in the carotid arteries; evaluate perfusion (blood flow) at or near the body surface, and body tissue damage at or near the surface (especially for burn assessment); and be used in a number of nondestructive evaluation applications. The device is based on low-power-pulsed microwave technology combined with a special antenna, signal processing/recognition algorithms, and a disposable cap worn by the patient that will facilitate accurate mapping of the brain and proper functioning of the instrument.

Generation of Low Work Function, Stable Compound Thin Films by Laser Ablation

Long N. Dinh, William McLean II, Mehdi Balooch,

Edward J. Fehring, Jr., Marcus A. Schildbach

U.S. Patent No. 6,235,615 B1

May 22, 2001

Generation of low-work-function, stable-compound thin films by laser ablation. Compound thin films with low work function can be synthesized by simultaneously laser ablating silicon, for example, and thermal evaporating an alkali metal into an oxygen environment. For example, the compound thin film may be composed of silicon, cesium, and oxygen. The work functions of the thin films can be varied by changing the ratios of silicon, alkali, metal, and oxygen. The low work functions of the compound thin films deposited on silicon substrates were confirmed by ultraviolet photoelectron spectroscopy. The compound thin films are stable up to 500°C as measured by x-ray photoelectron spectroscopy. Tests have established that for certain chemical compositions and annealing temperatures of the compound thin films, negative electron affinity was detected. The low-work-function, stable-compound thin films can be used in solar cells, field emission flat panel displays, electron guns, and cold-cathode electron guns.

Awards

For the first time in its history, the **American Optical Society** has awarded a fellowship posthumously. The society elected **Howard Powell**, a long-time Livermore researcher who died last November, as a **fellow**, recognizing him “for seminal contributions to the research and development of high-energy, high-peak-power, and high-average-power solid-state lasers for inertial confinement fusion, military applications and commercial utilization.”

The society also organized a Howard Powell Memorial Symposium on High Peak Power Laser Technology, which took place in May at the society’s Conference on Lasers and Electro-Optics in Baltimore, Maryland.

Powell worked at Livermore for 27 years. His numerous positions included being program leader of Laser Science and Technology. He also worked on the Nova, National Ignition Facility, and Petawatt laser projects. He was a corecipient of three R&D 100 Awards for laser research.

Dave Cooper, former associate director for Computation, has received the Department of Energy’s highest civilian recognition, the **Distinguished Associate**

Award. Cooper was presented with the award in May during a meeting of the President’s Information Technology Advisory Committee (PITAC) in Washington, D. C.

The award honors Cooper’s leadership of the DOE-National Nuclear Security Administration’s Accelerated Strategic Computing Initiative, the effort to simulate nuclear weapons performance with computer models. The citation on Cooper’s plaque reads: “In recognition of your outstanding leadership in high-performance computing. Your dedication to developing the advanced applications and high-performance computing platforms required for NNSA programs was instrumental in ensuring the nation’s security and advancing the frontiers in scientific computing.”

Although he stepped down from his Laboratory duties for health reasons, Cooper continues to serve on PITAC, which was created by an act of Congress to study a variety of information technology issues, from how access to government can be transformed through information technology to developing open-source software to advance high-end computing.

Annual Certification Takes a Snapshot of Stockpile's Health

Annual Certification is a formal assessment and reporting of the status of the nation's stockpile of nuclear warheads and bombs. The first Annual Certification was completed in February 1997, and the sixth is under way. The process is based on thorough technical evaluations by staff at the Lawrence Livermore, Los Alamos, and Sandia national laboratories; statements by their directors; and findings by the joint National Nuclear Security Administration/Department of Defense Project Officers Groups, the Commander-in-Chief of the Strategic Command, and the Nuclear Weapons Council. Ultimately, the secretaries of Energy and Defense transmit a written memorandum to the president (a document that since 2000 has been classified by law) describing the safety and reliability of the stockpile and whether a resumption of nuclear testing is needed. Several other agencies, groups, and advisory panels also play important roles. As part of the Annual Certification process, Lawrence Livermore and Sandia/California experts prepare four reports that describe the status of the four nuclear weapons designed by the two laboratories: the W62, W84, and W87 warheads and the B83 bomb. The draft reports involve a comprehensive review of the Laboratory's stockpile stewardship activities pertaining to each of the four weapon systems.

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Sensing for Danger

Intelligent and easily deployable sensor systems are important for many national security applications, particularly those relating to nonproliferation and tactical systems. Integrated networks of sensors have definite advantages over stand-alone detectors. At Livermore's Nonproliferation, Arms Control, and International Security Directorate, researchers are developing the special data-integration algorithms, advanced communications architectures, and wireless microsensors that comprise correlated sensor networks. These networks can interpret large volumes of data in real time to look for a pattern of sensor "hits" that are diagnostic of the expected threat. The correlation algorithm provides substantially improved detection while keeping the false-alarm rate low.

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Livermore Wins Three R&D 100 Awards



In *R&D Magazine's* annual competition for the "100 most technologically significant new products and processes," the Laboratory's winners are

- Manufacturing Laser Glass by Continuous Melting
- Gene Recovery Microdissection—A Process for Producing Chromosome Region-Specific Libraries of Expressed Genes
- LaserShot Marking System—High-Volume Labeling for Safety-Critical Parts

Also in September

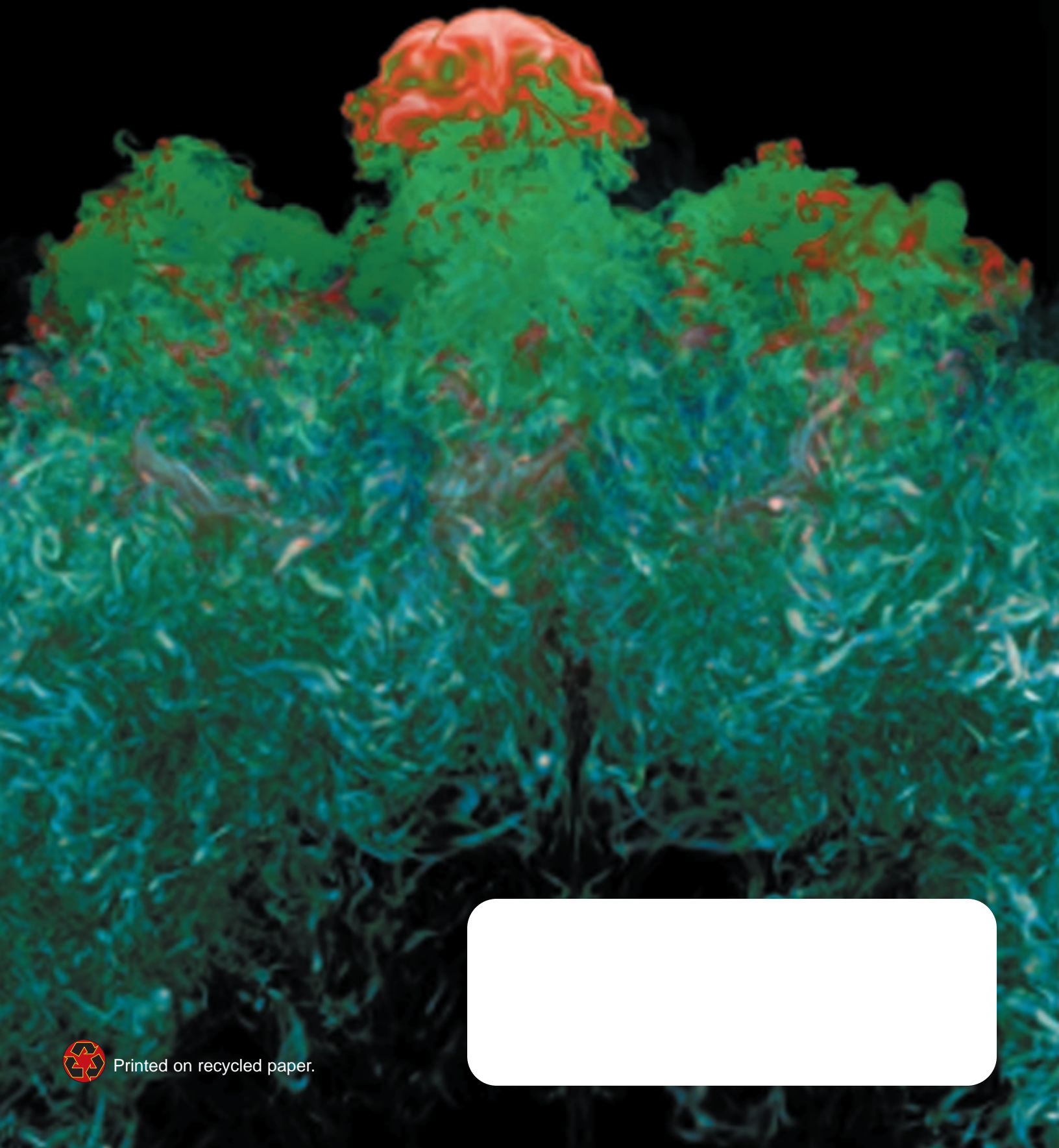
- *Livermore's Center for Global Security Research is exploring how new technologies in the wrong hands could threaten national security.*

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